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***Journal of Scientific and Engineering Research*, 2023, 10(9):23-29**

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Current Research Status of Liquid Injection Technology for Gas Control in Coal

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Abstract With the increasing exploitation of coal resources, mining mines are gradually shifting to deeper mines, and gas management will become more and more difficult, and in-coal fluid injection is a very effective method to solve the gas enrichment in coal seams. This paper analyzes the three widely used technologies of water injection in coal, single/complex surfactant injection, and water-based fracturing fluid injection, analyzes the current research status and the mechanism of each of them, and provides a new idea for the application of liquid injection in coal to control gas in the future to cope with the complex conditions of coal body and the difficulty of gas management.

Keywords Coal; fluid injection in coal; current status of research

1. Introduction

In recent years, the production of coal in China has been growing gradually, which greatly meets the needs of social development. Throughout the current coal production and demand, China is still in an important period of infrastructure construction, as well as an important stage of further development of urbanization and industrialization, so in the future for a long period of time, coal resources will still occupy a dominant position in energy [1]. However, with the increase in the depth of coal mining, the "three high" characteristics of the coal and gas storage environment become more and more prominent, and the accompanying problems such as the increase in the gas pressure and gas content of the coal seam and the increase in the amount of gas outflow, which leads to the gas concentration exceeding the limit, have become prominent, seriously restricting the sustainable, stable and healthy development of coal mines [2].

After entering deep mining, under the influence of high stress and high permeability pressure, the permeability of coal is low and the permeability is poor, and it is difficult to effectively reduce the gas content of the mined coal seam by using the traditional drilling gas extraction method. Therefore, to address the problems of low gas extraction concentration in the drilled holes of coal seams and difficulty in reducing the gas content of mined coal seams that exist in most deep mines, many scholars have analyzed the way of gas transport in the coal, and attempted to research a liquid to reduce the gas content of mined coal seams by injecting liquid into the mined coal seams to achieve the goal of reducing the gas content of mined coal seams under the influence of high stress and high osmotic pressure. In this way, a liquid can be injected into the mined coal seam to reduce the gas content of the mined coal seam. However, the effect of using coal seam liquid injection to reduce the coal seam gas content is closely related to the nature of the foreign liquid, and some scholars have found that injecting water [3-4], surfactants [5-6], fracturing fluids [7], and viscous liquids [8] into coal can effectively inhibit gas dispersion or increase the permeability of the coal seam, so the effect of these four liquids on the desorption of gas has aroused a great deal of research interest among scholars. Therefore, the effect of these four liquids on gas desorption has aroused great interest among scholars. In this paper, we use the literature survey method to organize the exotic liquids used for coal seam liquid injection in recent years, analyze their physicochemical properties, and investigate the mechanism of various liquids affecting coal gas desorption. The research work can provide theoretical guidance and scientific basis for coal seam liquid injection, which is of great significance for preventing the gas concentration in the mining face from exceeding the limit and guaranteeing the safe production of coal mines.

2. Adsorption Mechanisms and Discharge Characteristics of Gas in Coal

2.1 Adsorption mechanism of gas in coal

Adsorption on solid surfaces can be divided into 2 types: physical adsorption and chemical adsorption. Coal bed methane is stored in the coal bed in adsorbed, free and dissolved states, and coal adsorption of methane releases a certain amount of energy, and the interaction process between coal and methane is typical of physical adsorption [9]. From a microscopic point of view, the nature of coal adsorption of methane is due to the existence of an unbalanced force field on the surface of coal pores, methane molecules and coal molecules physically adsorbed due to van der Waals' force, which is the result of the mutual attraction between carbon molecules and methane molecules and the adsorption of methane by coal is in accordance with the Langmuir's theory of adsorption of monomolecular layers, and the coal's adsorption capacity is a function of temperature, adsorbent mass, pressure, and the nature of the coal. At a certain temperature and adsorbent mass, the adsorption of gas by coal can be described by the Langmuir equation [10], namely:

$$V=V_LP/(P_L+P) \quad (1)$$

Where: V_L is the Langmuir volume, cm^3/g; P is the gas pressure at adsorption equilibrium, MPa; P_L is the Langmuir pressure, MPa. It can be seen that the physical adsorption between coal and methane is due to the action of van der Waals force, and the adsorption law is consistent with the Langmuir adsorption theory.

2.2. Discharge characteristics of gas in coal

Most scholars believe that the gas discharge process of coal is a desorption-diffusion-seepage process. Regarding the gas discharge law of coal, Britain, the former Soviet Union, West Germany, Poland, France, Australia, Japan, and the Fushun Branch of the China General Research Institute of Coal Science, the Chongqing Branch, and the Henan University of Science and Technology have carried out a large number of experimental and theoretical modelling simplification studies, and proposed a series of empirical formulas for the gas desorption law [11].

The diffusion process of gas in coal has been shown that free gas exists in the state of free gas molecules in the large pores and fissures of the coal seam, while adsorbed gas exists inside the microporous structure [12-14]. The diameter of the gas molecule is 4.14 Å, and it can move in the micropores and fissures of the coal seam [15]. When the width of the fissure and pore diameter is greater than 10^{-7}m, it is laminar movement, when it is less than 10^{-7} molecules can not move freely, its movement is not determined by the pressure difference but by the concentration difference, under the action of the concentration difference, it diffuses into the fissure in the form of single-phase gas, which is diffusive movement [16-19]. For the diffusion model of gas, Fick's law of diffusion in mass transfer is generally quoted. The fluid molecules in the diffusion system move from high concentration to low concentration, and the diffusion velocity is linearly proportional to the concentration gradient of the fluid. For the diffusion process, methane molecules are classified into Fick type, transition type and Knudsen type according to their mean free range and the relative size of the pore size [20,21].

Seepage refers to the flow of fluids within a porous medium [22] From the structure of coal and gas storage, when the pressure in a certain area changes, there are both diffusion field of desorption and diffusion within the solid and seepage field of flow through large pores and fissures. Research on seepage modelling for gas-containing coal is fundamental in the field of mine gas extraction technology. Since the 1960s, many experts and scholars in China have been exploring the seepage model of gas-containing coal for more than half a century, and have developed linear seepage theory, diffusion theory, nonlinear seepage theory, and multi-physical field coupling theory, etc. [23].

3. Types of fluid injection in coal and its mechanism of action

3.1 Research Status of Coal Seam Water Injection for Gas Control

Coal seam water injection was first developed to solve the problem of coal dust in the coal mining face, and later some scholars found that the presence of water in the coal seam has a certain effect on the desorption characteristics of gas [24]. The physical effects of water on the gas after it enters the coal are extremely complex. The effect of water on gas varies due to differences in parameters such as coal seam gas content, gas pressure and coal seam permeability. The effect of water on the desorption of gas in coal is generally considered to be mainly in the two aspects of "displacement [25]" and "hydrolocking [26]". In coal seams with low gas pressure and good permeability, the gas exists mainly in the free state. Water can drive the free gas out of the cracks and pores of the coal body, occupy the crack channels, and play the role of driving out the gas. Wu

Jiahao et al [27] carried out a study on the effect of self-absorbing moisture on gas desorption in coal on anthracite from Jincheng Yonghong Coal Mine, and in the study of displacement desorption, it was found that with the increase of water, the gas in the coal was gradually displaced, and the amount of gas desorption was positively correlated with the water content.
In addition, after water enters the coal seam, it occupies the pores of the coal body according to the order of large pores, medium pores and finally into micropores , and seals the gas in the microporous fissures, which plays the role of water locking and thus reduces the amount of gas gushing out of the working face. Chen Xiangjun [28] carried out an experimental study on the effect of high-pressure water injection on gas desorption in granular coal, and the results of the study showed that there was a "water-placing gas" effect in the process of water injection, but in the stage of gas desorption in the coal seam unloading, the presence of water will play a significant inhibitory role in gas desorption; Chen Xuexi[29] carried out an experimental study on the effect of different water injection pressures on gas desorption in gas-containing coal, and the results showed that the amount of gas desorption decreased with the increase of water injection pressure. Xiao Zhiguo [30] found that with the increase of water, the desorption of gas in coal was slowed down, and the slowing down rate was related to the particle size of the coal samples, which indicated that the water inhibited the desorption of gas.
In summary, the mechanism of coal seam water injection to reduce the gas content of the working face is that, from the beginning of water injection, high-pressure water will fracture the coal body, increase the pore fissure of coal, and under the action of water pressure, high-pressure water enters into the coal body to drive out the free gas in the coal body, and the gas in the coal seam will be gushed out in large quantities, with the gradual injection of the amount of water, the water occupies the pores of the coal body in accordance with the sequence of large holes, medium holes and finally micropores and the gas in the microporous fissures is desorbed from the microporous fissures of the coal body. The gas in the microporous fissures is blocked, so that the adsorbed gas can not be transported out of the coal seam after transforming into the free state, which slows down the release of the free state gas, and plays a water-locking effect, and ultimately, the free state gas is driven away to the neighbouring seams in advance due to the displacement effect of the water before mining, which improves the concentration of the gas extracted from the neighbouring extraction holes, and effectively reduces the content of the coal seam's free state gas. At the same time, the gas in the adsorption state is effectively reduced, and at the same time, the gas in the adsorption state, due to the hydrolock effect, after its transformation into the free state, the release is inhibited by the water and cannot be rapidly gushed out from the coal, thus reducing the peak value of gas gushing out when the coal body falls, and avoiding the gas exceeding the limit.

3.2 Current Research Status of Coal Seam Injection Single/Compound Surface Gas Control

Surfactants were firstly applied to wetting the coal body, and the effect of pure water on dust reduction at the working face is limited in the coal seam water injection technology, especially in the coal body with high degree of metamorphism, it is difficult for pure water to wet the coal body, and adding surfactants to the water can effectively reduce the surface tension of the water and the contact angle with the coal, so as to make it better invade into the coal seam.In 1990's, the Chinese researchers began to carry out experimental research on adding surfactants to water injection of coal seams in some mining areas. In the 1990s, Chinese researchers began to carry out experimental studies on adding surfactants to water injection in coal seams in some mines. Zhang Chaoying [31], Chen Jinyu [32], Xiao Puchao [33], Miao Xueyu [34] and others, in response to the problems of gas management in specific mines, used the method of pressurised injection of surfactants into coal seams on site to solve the problem of unloading coal seams effectively, and confirmed that the surfactants could inhibit the gas outflows, and reduce the risk of protrusion of the uncovered coal. On this basis, scholars have carried out research on the wettability of coal and the inhibition mechanism of gas desorption in coal by single surfactant, inorganic salt compounded surfactant, and compounded solution of two surfactants, and have achieved many results.
Yin Zhihong [35] added different mass concentrations of sodium dodecylbenzene sulfonate (anionic) and nylon (nonionic) surfactants to anthracite coal on the basis of a large number of experimental test data, and found that these two surfactants can significantly improve the wettability of coal, so that the water can easily enter into the tiny pores. Zhang [36] used 0.025% JFC penetrant (nonionic surfactant) to invade coal samples, and it was concluded that the penetrant solution could reduce and delay the desorption rate of coal gas after immersion; Lin Haifei et al. [37] used the compound solution of SDBS and $CaCl_2$ to study the inhibitory effect of inorganic salts compounding solution on the desorption of coal gas, and it was concluded that the compound solution of SDBS and $CaCl_2$ could Effectively reduce the surface tension of pure water, the contact angle of coal samples, the higher the mass concentration of $CaCl_2$, the greater the inhibition efficiency; Weng Anqi [38] used inorganic salts NaCl, Na_2SO_4, $MgCl_2$ and other three kinds of inorganic salts as a synergistic agent and anionic surfactants, through the reverse osmosis of coal experiments concluded that the inorganic salts as a synergistic agent can effectively improve the anionic surfactant wetting ability, of which the synergistic effect of NaCl is

the best. NaCl has the best effect.

In recent years, many scholars have studied the use of two or more surfactants in coal seam water injection, and from the experimental results, it can be concluded that the wetting effect of the coal body and the gas inhibition effect are significantly better than a single surfactant. Zhu Kingland [39] through the comparison of single solution and compound solution on the wettability of coal and inhibit coal gas outflow experiments, it is concluded that the surface tension and contact angle is a measure of the surfactant solution in the object interface performance of the main parameters, the critical micelle concentration is a huge change in the performance of the solution of the turning point, the compound solution of the surface tension of the single solution than the significantly lower and can significantly reduce the amount of gas outflows. Hufu et al [40] used various anionic surfactants (SRJ-1, SRJ-2, SRJ-5, SRJ-6) and nonionic surfactant SRJ-4 and amphoteric surfactant SRJ-3, and by comparing the wetting effect of single active agent and compounded active agent on the coal body, it was concluded that the compounded wetting performance was superior to that of the monomer wetting agent; Liu Baoli [41] used SDS, CDEA, CTAB and other three surfactants, according to different ratios of two two compounding, research on the effect of compounding liquid on gas desorption, the study concluded that the effect of the compounding of SDS and CDEA on the rate of gas dissipation is better than the other two ways, and the three ways of compounding in the conditions of equal mass concentration, the effect of the volume ratio of 3:1 is the most obvious; Jiang Li [42] used four kinds of biosurfactants (tea saponin, Sapindus, sucrose ester, lipopeptide) in different volume ratios of two-two mixtures, to study the wettability of the mixtures of biosurfactants on the coal body, and the study showed that the critical micellar concentration of 1g/L of Sapindus and lipopeptide mixtures in the volume ratio of 1:1, the solution wettability is the best, and the solution wettability is the worst in the volume ratio of 1:1 of Sapindus and lipopeptide mixtures in the volume ratio of 0.2 g/L.

Summarising the experience of previous research, it can be concluded that ① surfactants can reduce the surface tension of water and accelerate the speed of water infiltration into the coal body in order to achieve the purpose of inhibiting the desorption of coal body gas. The wettability and inhibition of gas desorption of coal body by the compound solution of inorganic salt and single surfactant and the compound solution of two surfactants are better than that of single surfactant solution.

3.3 Research Status of Coal Seam Fracturing Fluid Injection for Gas Control

The application of fracturing fluid to control gas is mainly inspired by oil and gas extraction. Fracturing fluid has the advantages of good sand-carrying, rubber-breaking, low damage and simple construction, etc. In oil and gas extraction, a high-pressure, large-displacement pump is used to inject fracturing fluid into the oil formation at a pressure greater than the absorption capacity of the oil formation by using the principle of liquid pressure transfer, and the pressure inside the wellbore rises gradually, so as to hold high pressure at the bottom of the well, when the pressure is greater than the ground stress and the tensile strength of formation rock near the wall, cracks are produced in the formation near the bottom of the well. When this pressure is greater than the geostress near the well wall and the tensile strength of the formation rock, cracks are created in the formation near the bottom of the well, and the sand-carrying fluid with proppant continues to be injected, the cracks extend forward and are filled with proppant, and after the well is shut down, the cracks are closed on the proppant, so that sand-filled cracks of certain geometric dimensions and high flow-conducting capacity are formed in the formation near the bottom of the well, so as to achieve the purpose of increasing the production and injecting more oil. With reference to this principle, for coal seams with poor permeability, water-based fracturing fluids can also be injected into such seams to increase the porosity of the coal body as a means to increase the concentration of gas extraction from the borehole, so that gas can be extracted more easily for the purpose of reducing the gas content of the coal seam, and the four types of fracturing fluids that have been most widely used at present are activated water fracturing fluids, foam fracturing fluids, clean fracturing fluids, and linear gel/frozen gel fracturing fluids.

Table 1: Comparison of the performance of various water-based fracturing fluids

	Composition	Advantages	Disadvantages	Application effects
Activated water fracturing fluid	N_2, CO_2 or liquid phase and foaming agent	Lower viscosity and price	Higher filtration loss, poorer rheological properties, high friction resistance, difficult to control crack patterns	Less damage to the coal seam, simple liquid mixing process, low cost
Foam fracturing fluid	Surfactants and potassium	Low liquid content, high	Poorly equipped and costly	Significant increase in yield

	chloride	viscosity, high sand capacity		
Clean fracturing fluid	Viscoelastic surfactants	Low filtration loss, virtually no residue, low friction	High cost	Smaller applications, significant yield increases
Linear gel/freeze gel fracturing fluid	Linear or lyophilised gel	High viscosity and sand-carrying capacity	High solid-phase sand content, clogging of pores, serious injury to the coal seam	Difficulty in breaking glue and returning to the drain

Adopting the method of injecting water-based fracturing fluid into coal seams to manage gas can effectively solve the problem of gas enrichment in coal seams, and has been widely used in many mining areas in China, and the effect is remarkable. Li Ting [43] and others in the coal seam field hydraulic fracturing test, the construction of 10 coalbed methane wells were successful, and found that the clean fracturing fluid can effectively improve the effect of gas pumping.

4. Prospects of gas injection technology in coal

Regardless of whether it is water injection, single/complex surfactant injection or fracturing fluid injection to control gas, the main principle is to drive out the gas, block the transportation channel after the adsorbed gas is transformed into the free state, increase the pore space and fissure in the coal seam, and improve the concentration of gas extraction in the drilling holes in order to reduce the enrichment of gas in the coal seam, which is from the point of view of making the free state gas easier to be extracted, and not being able to be released after the adsorbed gas transforms into the free state. From the point of view of the gas, the main gas is methane, which is a kind of gaseous organic matter. In the future, in the technology of injecting liquid into the coal to control the gas, one or several kinds of liquids (organic reagents) that can easily dissolve the gas can be added to the injected liquid, and by using the principle of similarity and solubility, the gas in the coal seam will be absorbed into the solution to form a gas hydrate, which can fix the gas in the solution, and through the pumping pipe, the solution will be pumped to the well specifically designed for the absorption of the gas. Through the extraction pipeline, the gas-absorbing solution is pumped to the bucket specially used for storing the solution in the well, and then the gas in the solution is stripped out through certain technical means, and the solution can also be reused to reduce the cost of treatment.

With the increasing exploitation of coal resources, mining mines will gradually shift to deep mines, the deeper the coal seam, the greater the difficulty of mining, prevention and control of more difficulties, relying on the existing gas prevention and control technology may be difficult to safely and effectively ensure the safety of coal mining, so the future of coal mine gas prevention and control technology should seek diversified development, from more perspectives, to think about ways to prevent and control the mine gas overload/highlighting.

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